Engineering Analysis: Cost-Efficiency Curves

Commercial Unitary Air Cooled Air Conditioners and Air Source Heat Pumps

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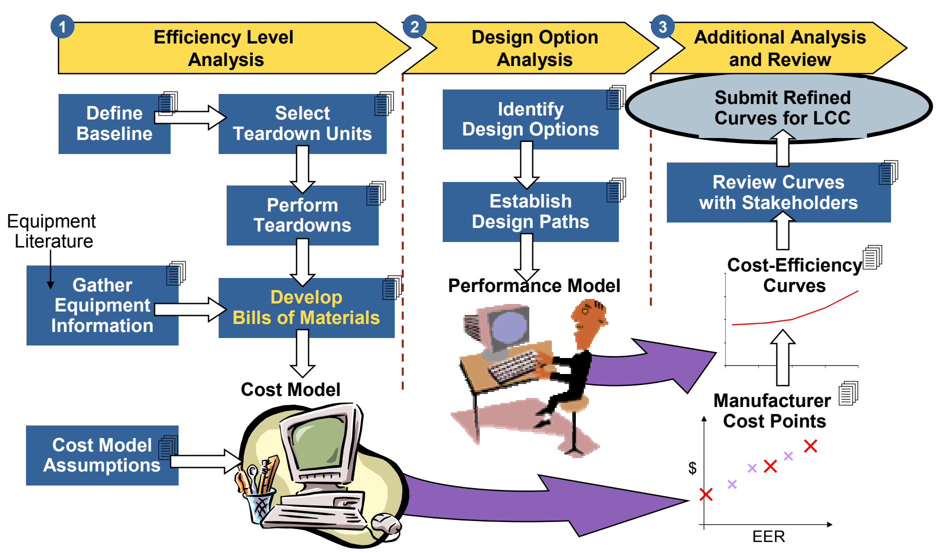
Cost-efficiency curves[1] were developed as part of the engineering analysis phase of DOE standards development for the commercial unitary air conditioner rulemaking process.

The purpose of this presentation is to:

- ☑ Review the scope of the Engineering Analysis
- ☑ Review the methodologies used to create the cost-efficiency curves
- ☑ Present the R-22 cost-efficiency curves that will be incorporated into the LCC analysis for the ANOPR
- ☑ Present conclusions from the alternative refrigerant R-410A cost-efficiency analysis

[1] "Cost" for the purposes of this analysis refers to the total equipment cost, consisting of fixed and variable production costs, plus corporate overhead (S,G&A, transport, profit), as described on page 6. The cost-efficiency curves discussed here do not represent the final cost to the end-user. This "end-user cost" incorporates distribution chain markups and is addressed in the separate LCC analysis.

We used three stages to create the cost-efficiency curves.



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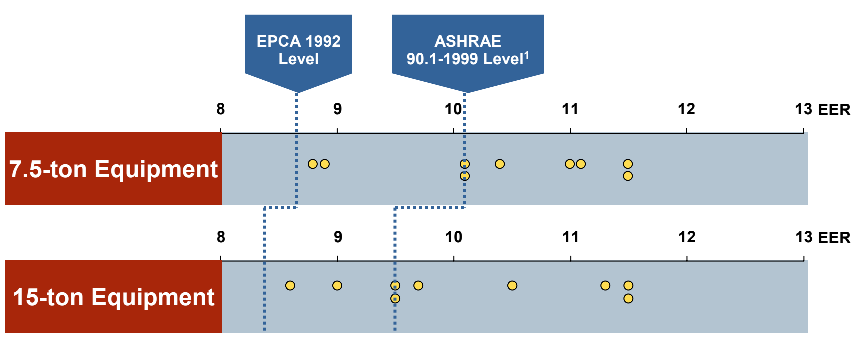
A total of 18 unitary air conditioners were analyzed, representing several different manufacturers and a wide range of EERs, and four units were selected for physical teardowns.



The 7.5- and 15-ton unitary air conditioners were selected in consultation with manufacturers because they represent high shipment volume air conditioners within the equipment capacity ranges under consideration.

Source: Product specifications from manufacturer's current product catalogs.

[1] Based on ASHRAE 90.1-1999 Mandatory Minimum EER, reduced by 0.2 for units having a heating section other than electric resistance heat.

The selected units are broken down (physically or using catalog/design data) to create a bill of materials that is fed into the TIAX cost model.

TIAX Cost Model Structure

Markup = 1.23[2]

Corporate Expenses
- Research and Development
- Net Profit
- General & Administration
- Warranty[1]
- Taxes
- Sales and Marketing

Net Profit
General Expense
Sales Expense
Shipping

Factory Cost

Fixed Costs
- Equipment and Plant Depreciation
- Tooling Amortization
- Equipment Maintenance
- Utilities
- Indirect Labor
- Cost of capital
- Overhead Labor

Variable Costs
- Manufactured Materials
- Purchased Materials
- Fabrication Labor
- Assembly Labor
- Shipping
- Indirect Materials

Factory Expense
Direct labor
Direct Materials

Total Equipment Cost

In the separate LCC analysis, the factory cost is used to determine the end-user cost after various supply-chain markups.

[1] Some manufacturers consider warranty a manufacturing cost, not a corporate expense.
[2] Based on analysis of industry corporate financial records.

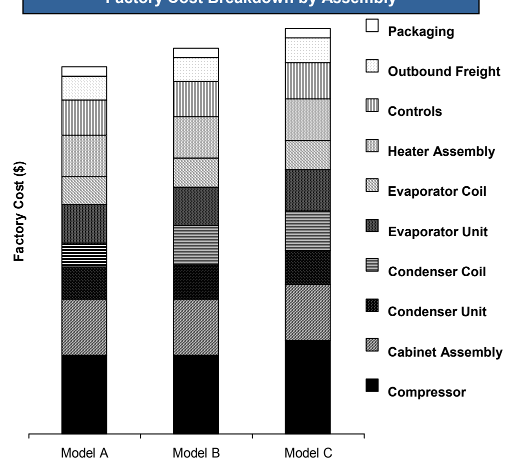
Individual cost models[1] were generated for each piece of equipment and reviewed by several individual manufacturers. Their feedback was used to refine the model.

Factory Cost Breakdown by Function

	Model A	Model B	Model C
Labor	$	$	$
Material	$	$	$
Overhead & Ship	$	$	$
Depreciation	$	$	$
TOTAL factory cost	**$**	**$**	**$**

ILLUSTRATIVE SAMPLE

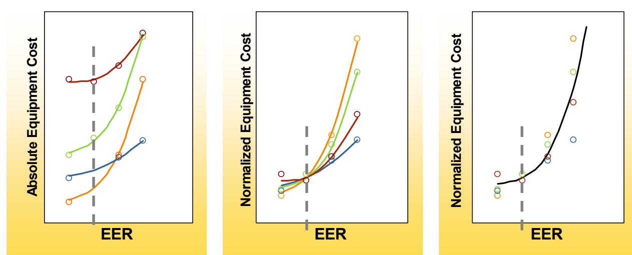
Factory Cost Breakdown by Assembly



[1] Data is business sensitive and considered proprietary.

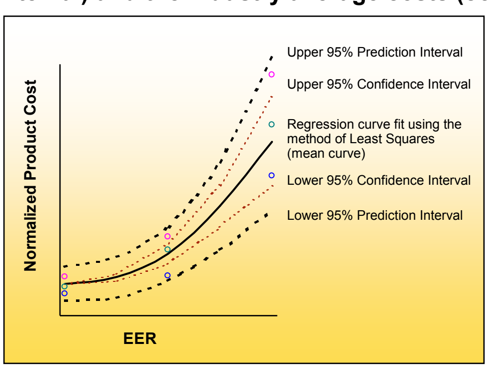
A three-step process was used to combine equipment cost data points and construct the cost-efficiency curve.

1. **We started by fitting an exponential curve[1] to each manufacturer's cost-efficiency points individually.**
2. **Then we normalized the data points so that each manufacturer curve intersected at the ASHRAE 90.1-1999 EER level[2].**
3. **Next, we fit an exponential curve to the normalized data points (all manufacturers), extending the curve slightly to 12 EER[3].**



[1] The nature of the cost-efficiency data suggests an exponential curve, so the data were fit to an exponential curve using the method of Least Squares.
[2] Some manufacturers do not have equipment at the ASHRAE 90.1-1999 levels.
[3] The accuracy of the curve's extension beyond available data is verified later by the design option analysis.

We established bounds for single air conditioner costs (prediction interval) and the industry average costs (confidence interval).



- At any given EER level the cost of a single air conditioner will equal the mean cost **+/- the prediction interval.**
- For any sample of air conditioners at a given EER level, their average cost will equal the mean cost **+/- the confidence interval.**

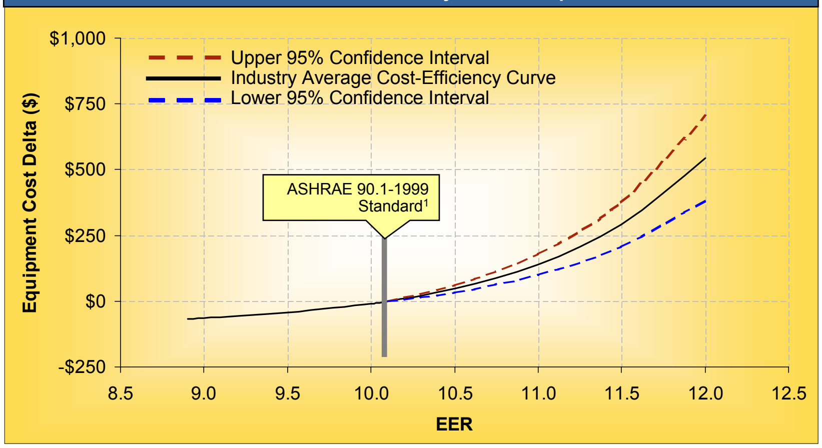
95% Prediction Interval (PI) represents the accuracy of predicting the cost of any single unit given its EER. If we were to pick any unit on the market, there is a 95% chance that its cost would fall within the prediction interval we created based on our sample.

95% Confidence Interval (CI) represents the accuracy of the mean regression curve-fit. If we were to sample any number of existing products at a given EER level and calculate their mean cost, there is a 95% chance that it would lie within the confidence interval we created based on our sample.

Efficiency Level Analysis Aggregate Curves *7.5-ton*

The industry average is represented by the resulting 7.5-ton cost-EER curve and is bounded by the confidence interval.

7.5-ton Cost-Efficiency Relationship

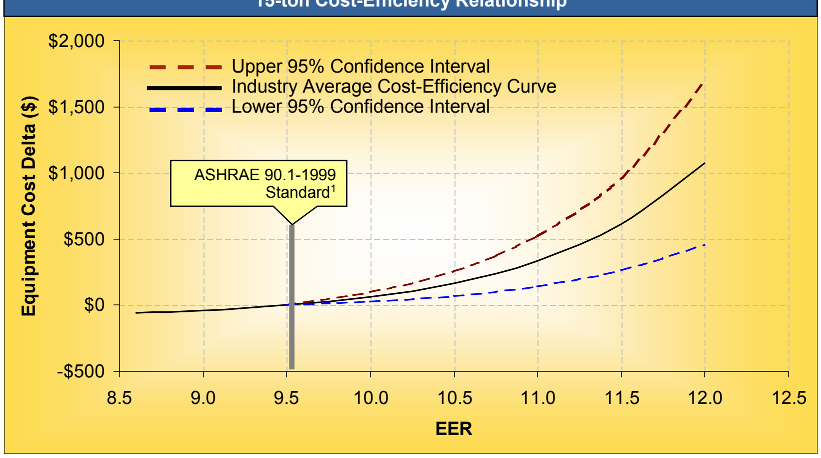


[1] Based on ASHRAE 90.1-1999 Mandatory Minimum EER, reduced by 0.2 for units having a heating section other than electric resistance heat..

Efficiency Level Analysis Combined Curves *15-ton*

The industry average is represented by the resulting 15-ton cost-EER curve and is bounded by the confidence interval.

15-ton Cost-Efficiency Relationship



[1] Based on ASHRAE 90.1-1999 Mandatory Minimum EER, reduced by 0.2 for units having a heating section other than electric resistance heat.

Using the same starting point, the cost of increasing EER is approximately 80% greater for 15-ton units than for 7.5-ton units.

Incremental Cost Deltas for the Mean Cost-Efficiency Curves			
EER Range	9-10 EER	10-11 EER	11-12 EER
15-ton Curve	$100	$272	$738
7.5-ton Curve	$55	$150	$406

* Numbers are rounded to the nearest whole dollar.

- It is important to compare the costs at similar efficiency level ranges. Because the curves are exponential, comparing incremental costs for different ranges of EER levels is misleading.
- The numbers in the above table represent the industry mean, and the ratio for individual manufacturers may vary considerably because of differences in design strategies and design constraints.

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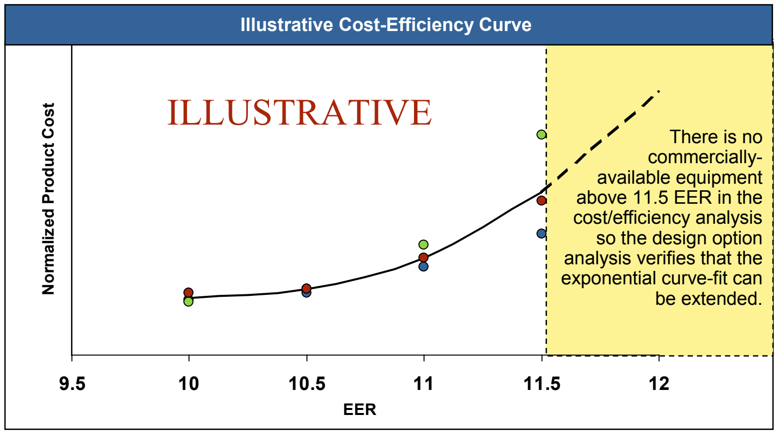
The design option analysis simulated equipment data points to validate the cost-efficiency curve at higher efficiency levels.



The design option points were not included in the regression used to create the cost-efficiency curves.

The design option process simulates existing equipment performance to establish baselines, then models the effect of various design options or design option combinations on the equipment's EER.

- We used the ORNL heat pump model for refrigerant-side heat transfer and mass balance calculations (for given compressor performance curves), using TIAX calculations and test data to adjust the UA (overall heat transfer coefficient) and pressure drop correction factors within the model.
- We used TIAX software to simulate air-side heat exchanger performance including UA and pressure drop.
- We used published fan and motor curves to calculate air-balancing and fan power draw.
- We used the TIAX cost model to estimate design option costs.

We calibrated our modeling process by matching the 7.5-ton standard-efficiency baseline model to the independent test data (from ITS).

	Predicted by Model	Measured by ITS Testing[1]	*Difference*
Capacity (Btu/hr)	91,037	92,741[2]	*-1.8%*
EER	10.33	10.45[2]	*-1.1%*
Compressor Power (W)	7,325	7,430 +/- 2.0%	*-1.4%*
Evaporator Blower Power (W)	910	880 +/- 2.0%	*+3.4%*
Condenser Fan Power (W)	575	562 +/- 2.0%	*+2.3%*
Evaporator Pressure (PSIA)	96.8	98.7 +/- 2.0%	*-1.9%*
Evaporator Temperature (°F)	48.8	50[2] (48.7 - 51.2)[3]	*-1.2 °F*
Condenser Pressure (PSIA)	279.2	282.2 +/- 2.0%	*-1.1%*
Condenser Temperature (°F)	121.3	122.1[2] (120.6 - 123.7)[3]	*-0.8 °F*

[1] Using Test "A" methods.
[2] Calculated from measured data.
[3] Range calculated from pressure error band.

New EER data points were established by modifying existing equipment using two design option approaches.

BASELINE | APPROACH | DESCRIPTION

An existing air conditioner is the starting point for the design process.

1 **Condenser Coil** → Increases either condenser area or depth while adjusting fan size, number of fans, motor size, subcool, and/or compressor capacity.

2 **Evaporator Coil** → Increases either evaporator area or depth while adjusting blower size, number of blowers, subcool, and/or compressor capacity.

EER Design Targets
7.5-ton → 10.5-EER and 12.0-EER
15-ton → 11.0-EER and 12.0-EER

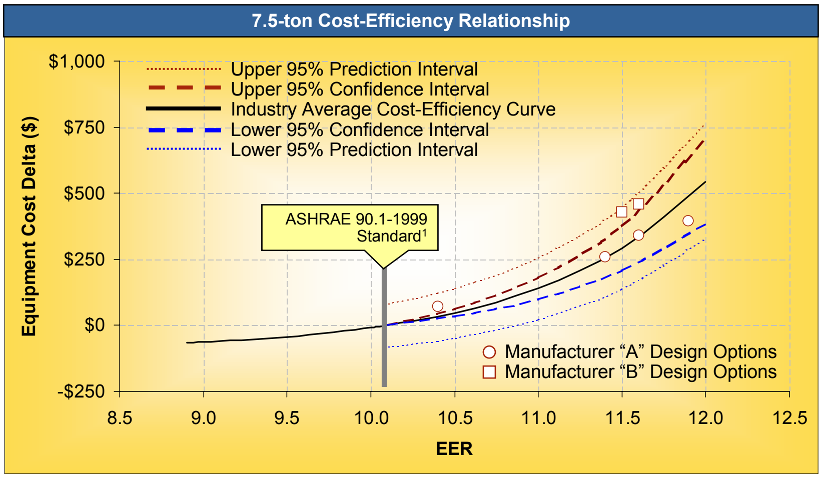
Modeling Guidelines

- Evaporator temperature <52°F
- SHR <0.75
- Condensing temperature >117°F
- Condenser exit temperature >102°F
- Condenser refrigerant $\Delta P <$ 10psi
- Condenser face velocity >200fpm
- Blower motor efficiency = 85%
- Condenser fan motor efficiency = 70%
- Maintain system capacity +/-2% vs. baseline

The design options were combined to reach the EER design targets while satisfying various modeling guidelines suggested by the manufacturers and based on TIAX expertise.

Design Option Analysis Design Options *Results*

The 7.5-ton design option data points for two representative manufacturers validate the curve at higher efficiency levels.



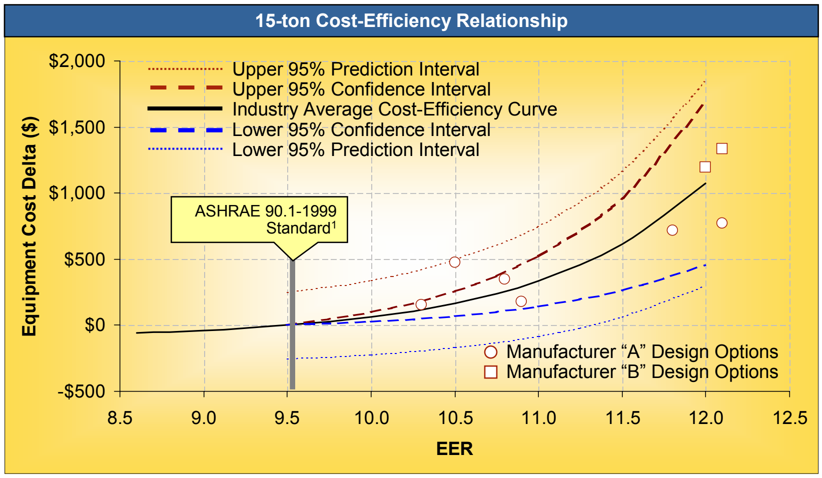
[1] Based on ASHRAE 90.1-1999 Mandatory Minimum EER, reduced by 0.2 for units having a heating section other than electric resistance heat.

Design Option Analysis Design Options *Results*

Detailed results from the design option analysis for one manufacturer illustrate how we achieved EER levels above 11.0 for the 7.5-ton units.

Approach	Baseline Model	Condenser Area +50% Area	Condenser Depth +1 Row	Area Combination +50% Cond., +25% Evap.
Δ EER	--	+0.6 EER	+0. 4 EER	+0.9 EER
Physical Changes	BASELINE	**box:** +70% volume **condenser:** +50% area **compressor:** 2 x 42.0 kBtu/hr	**condenser:** +1 row **compressor:** 2 x 42.0 kBtu/hr	**box:** +70% volume **condenser:** +50% area **evaporator:** +25% area **compressor:** 2 x 40.6 kBtu/hr
Performance Characteristics	**Tc** = 121.0 F **Te** = 48.9 F **Subcool** = 10.8 F **Superheat** = 20 F **Compressor:** 6883 W **Fan:** 620 W **Blower:** 700W SHR = 0.728	**Tc** = 117.8 F **Te** = 48.8 F **Subcool** = 11.7 F **Superheat** = 20 F **Compressor:** 6533 W **Fan:** 560 W/ +300 CFM **Blower:** 700W SHR = 0.729	**Tc** = 118.5 F **Te** = 48.9 F **Subcool** = 11.9 F **Superheat** = 20 F **Compressor:** 6545 W **Fan:** 655 W/ -300 CFM **Blower:** 700W SHR = 0.730	**Tc** = 117.4 F **Te** = 50.7 F **Subcool** = 11.2 F **Superheat** = 20 F **Compressor:** 6289 W **Fan:** 560 W/ +300 CFM **Blower:650**W SHR = 0.739

The 15-ton design option data points for two representative manufacturers validate the curve at higher efficiency levels.



[1] Based on ASHRAE 90.1-1999 Mandatory Minimum EER, reduced by 0.2 for units having a heating section other than electric resistance heat.

Detailed results from the design option analysis for one manufacturer illustrate how we achieved EERs above 11.5 for the 15-ton units.

Approach	Baseline Model	Condenser Area +10% Area	Condenser Depth +1 Row	Evaporator Depth +1 Row
Δ EER	--	+0.5 EER	+0. 6 EER	+0.3 EER
Physical Changes	BASELINE	**condenser:** +10% area **condenser fans:** +2" diameter **compressor:** 1 x 58.5 kBtu/hr 1 x 115.0 kBtu/hr	**condenser:** +1 row **condenser fans:** +2" diameter **compressor:** 1 x 58.5 kBtu/hr 1 x 115.0 kBtu/hr	**evaporator:** +1 row **compressor:** 1 x 58.5 kBtu/hr 1 x 117.0 kBtu/hr
Performance Characteristics	**Tc** = 125.37 F **Te** = 51.5 F **Subcool** = 16.4 F **Superheat** = 10 F **Compressor:** 13,418 W **Fan:** 1070 W **Blower:** 1240 W SHR = 0.722	**Tc** =120.3 F **Te** =51.5 F **Subcool** =14.0 F **Superheat** =10 F **Compressor:**12,344 W **Fan:**1450 W/+2,800 CFM **Blower:**1240 W SHR =0.723	**Tc** =119.8 F **Te** =51.4 F **Subcool** =14.3 F **Superheat** =10 F **Compressor:**12,283 W **Fan:** 1365 W/+1,600 CFM **Blower:** 1240 W SHR =0.723	**Tc** =125.0 F **Te** =52.7 F **Subcool** =16.2 F **Superheat** =10 F **Compressor:**13,115 W **Fan:** 1070 W **Blower:**1105 W/-300CFM SHR =0.719

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In 2010, R-22 will be phased out in new equipment. The Department examined two potential replacement refrigerants - R-407C and R-410A - to determine which would be the more likely replacement for the market segment under consideration.

R-407C

- **Pros:** Similar pressure-temperature relationships to R-22, make it a more straightforward replacement for R-22 than R-410A.
- **Cons:** Lower efficiency than R-410A under most conditions relevant to market segment.

R-410A

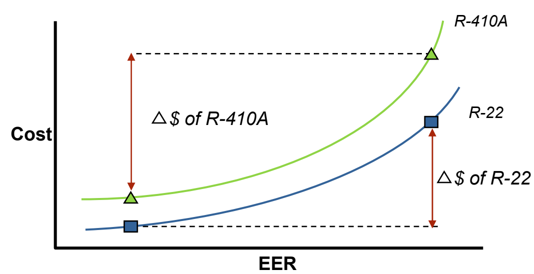
- **Pros:** Manufacturers interviewed by DOE generally agreed that R-410A would be the most likely replacement for R-22 in this market segment; higher efficiency than R-407C under most conditions relevant to this segment.
- **Cons:** Operates at higher pressures than R-22 and R-407C, requiring substantial equipment re-design (including maintenance equipment).

Based on these factors, the Department concluded that R-410A[1] is the most likely replacement for R-22.

[1] *At least two companies currently produce R-410A in the U.S.; additional producers outside the U.S.*

Because the new efficiency standard would take effect just as R-22 is being phased out, the engineering analysis needs to consider how the cost-efficiency behavior of R-410A and R-22 products might differ.

- .The properties of R-410A are very different than those of R-22:
  - operates at a higher pressures;
  - requires modification of existing refrigeration components.
- It is important to recognize that the critical parameters in the analysis are the cost differential between baseline and high efficiency units (rather than absolute cost) and whether this cost delta differs for R-410A vs. R-22 equipment.



A three-step process was used to analyze the impact of R-410A on the cost-efficiency curves.

1 Design Baseline R-410A Equipment

- To provide general engineering guidance, compare designs of R-22 and R-410A equipment in commercially available smaller packaged units (e.g. 5 tons).
- Using the same performance model as the R-22 equipment, replace the compressor with a comparable R-410A unit.
- Modify design through changes to heat exchangers and other components to match the performance of R-22 equipment.

2 Model EER and Costs

- Modify the baseline models through changes to heat exchangers and other components to reach target EER levels.
- Using the cost model, estimate the costs of the baseline and modified R-410A models.

3 Develop Cost-EER Curves

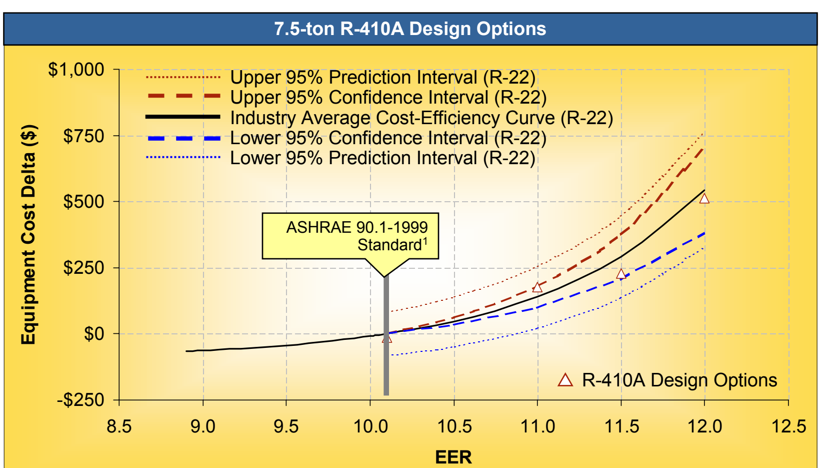
- Develop cost-efficiency curves, similar to the R-22 curves.
- Compare the *slope* of the R-22 curves with the *slope* of the R-410A curves and determine if further analysis is required.

In completing the preliminary R-410A analysis, a number of assumptions were made regarding the major components of the unitary equipment.

- Although design pressures are higher, the diameter and thickness of the copper tubing remains the same[1].
- The R-410A compressors will cost about 4% more in the long-term (i.e. high volume production) than R-22 compressors with similar capacity[2].
- R-410A scroll compressors are less efficient than comparable R-22 scroll compressors, but more efficient than low-efficiency R-22 reciprocating compressors[3].
- The higher heat-transfer coefficients of the R-410A allow slightly lower condensing temperatures than possible with R-22[4].
- The evaporating temperature limits for R-410A system were the same as the R-22 system[5].
- The long-term cost of R-410A refrigerant in bulk will be approximately $3/lb[6].

[1] Interview with manufacturer and comparison of R-22 and R-410A equipment in smaller packaged units.
[2] Personal communications with a leading compressor manufacturer.
[3] Based on manufacturer test data from catalogs.
[4] Minimum condensing temperature reduced to 116F versus 117F for R-22, based on LMTD calculations with 15% higher heat transfer coefficient.
[5] Driven by the need to maintain an appropriate sensible heat ratio (SHR).
[6] Personal communications with leading refrigerant manufacturer.

The 7.5-ton R-410A design option points based on a representative design follow a trend that is similar to the R-22 cost-efficiency curve.

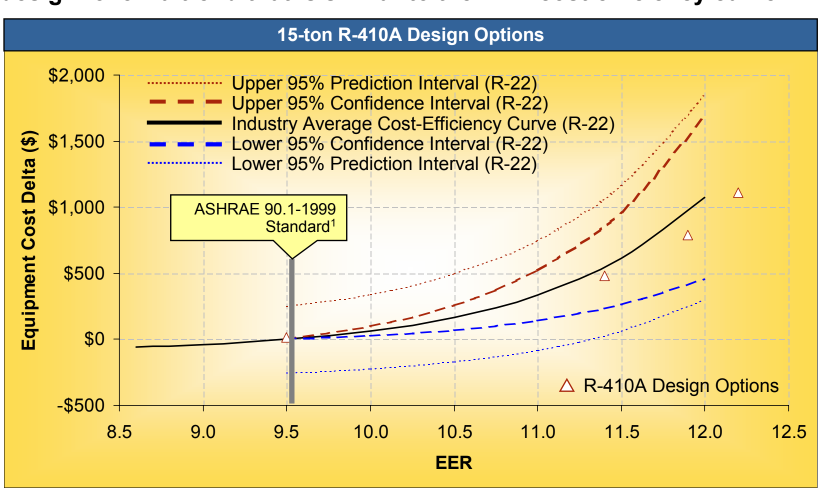


[1] Based on ASHRAE 90.1-1999 Mandatory Minimum EER, reduced by 0.2 for units having a heating section other than electric resistance heat.

Detailed results from the R-410A design option analysis illustrate how we simulated 7.5-ton R-410A equipment.

Approach	Baseline Model	Condenser Only 20 ft² Area, +1 Row	Cond. & Evap. Prev. step, +1 Row evap	Cond-Evap-ECM Prev. step+ECM +12%Ev.
Δ EER	Baseline = 10.1 EER	+0.9 EER	+1.4 EER	+1.9 EER
Model Results	10.3 EER 90,350 Btuh	11.2 EER 90,760 Btuh	11.7 EER 90,800 Btuh	12.2 EER 90,300 Btuh
Physical Changes	BASELINE	**condenser:** +21%area/+1 row **compressor:** 2 x 41.2 kBtu/hr	**condenser:** +21% area/+1 row **evaporator:** +1 row **compressor:** 2 x 41.2 kBtu/hr	**condenser:** +21% area/+1 row **evaporator:** +1 row **condenser fans:** ECM motors **evaporator blower:** **ECM motor** **compressor:** 2 x 41.2 kBtu/hr
Performance Characteristics	**Tc** = 122.8 F **Te** = 48.3 F **Subcool** = 12.9 F **Superheat** = 20 F **Compressor:** 7222 W **Fan:** 620 W **Blower:** 910W SHR = 0.728	**Tc** = 116.1 F **Te** = 48.2 F **Subcool** = 5.8 F **Superheat** = 20 F **Compressor:** 6580 W **Fan:** 610 W/ -15 CFM **Blower:** 910W SHR = 0.727	**Tc** = 116.6 F **Te** = 50.8 F **Subcool** = 10.6 F **Superheat** = 20 F **Compressor:** 6149 W **Fan:** 610 W / -15 CFM **Blower:**960W SHR = 0.743	**Tc** = 116.3 F **Te** = 51.6 F **Subcool** = 10.2 F **Superheat** = 20 F **Compressor:** 5989 W **Fan:** 520 W / -15 CFM **Blower:**870W SHR = 0.748

The 15-ton R-410A design option points based on a representative design follow a trend that is similar to the R-22 cost-efficiency curve.



[1] Based on ASHRAE 90.1-1999 Mandatory Minimum EER, reduced by 0.2 for units having a heating section other than electric resistance heat.

Detailed results from the R-410A design option analysis illustrate how we simulated 15-ton R-410A equipment.

Approach	Baseline	Condenser Only 27% Area, +1 Row	Condenser Max 57% Area, 4 row	Max + ECM 57% Area, 4 row
Δ EER	Baseline = 9.5 EER	+1.9 EER	+2.4 EER	+2.7 EER
Model Results	9.7 EER 182,540 Btuh	11.6 EER 174,120 Btuh	12.1 EER 180,360 Btuh	12.4 EER 180,450 Btuh
Physical Changes	BASELINE	**box:** **+47% volume** **condenser:** +27% area/+1 row **compressor:** 1 x 103.0 kBtu/hr 1 x 55.0 kBtu/hr	**box:** **+47% volume** **condenser:** +57% area, +1 row **compressor:** 3 x 50.5 kBtu/hr	**box:** **+47% volume** **condenser:** +57% area, +1 row **condenser fans:** ECM motors **evaporator blower:** ECM motor **compressor:** 3 x 50.5 kBtu/hr
Performance Characteristics	**Tc** = 126.3 F **Te** = 51.0 F **Subcool** = 18.2 F **Superheat** = 10 F **Compressor:** 15890 W **Fan:** 1660 W **Blower:**1240W SHR = 0.721	**Tc** = 118.2 F **Te** = 51.1 F **Subcool** = 14.1 F **Superheat** = 10 F **Compressor:** 12660 W **Fan:** 1600 W/ +2,500CFM **Blower:**1240W SHR = 0.724	**Tc** = 116.1 F **Te** = 51.1 F **Subcool** = 11.7 F **Superheat** = 10 F **Compressor:** 12098 W **Fan:** 1545 W/ +2,900CFM **Blower:**1240W SHR = 0.724	**Tc** = 116.1 F **Te** = 51.1 F **Subcool** = 11.7 F **Superheat** = 10 F **Compressor:** 12098 W **Fan:** 1320 W/+2,900 CFM **Blower:**1170W SHR = 0.724

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The results of the efficiency level analysis and the design option analysis have established a cost-EER relationship that is used as input to the LCC analysis.

- Our results have been reviewed in-depth with several manufacturers, and their feedback has been incorporated.
- Although the absolute costs of R-410A systems exceed those of R-22 systems, our analysis indicates that the slope of the R-410A cost-efficiency curve is similar to that of the R-22 curve (i.e. cost delta per incremental EER increase is approximately equal). Consequently, we have found no justification for shifting the R-22 cost-efficiency curves to account for the implementation of R-410A.
- We provided LBNL with the industry average cost-efficiency curves and 95% confidence intervals generated for R-22 systems so they may perform the LCC analysis in preparation for the ANOPR.